



# A common-path, multi-channel heterodyne laser interferometer for sub-nanometer surface metrology

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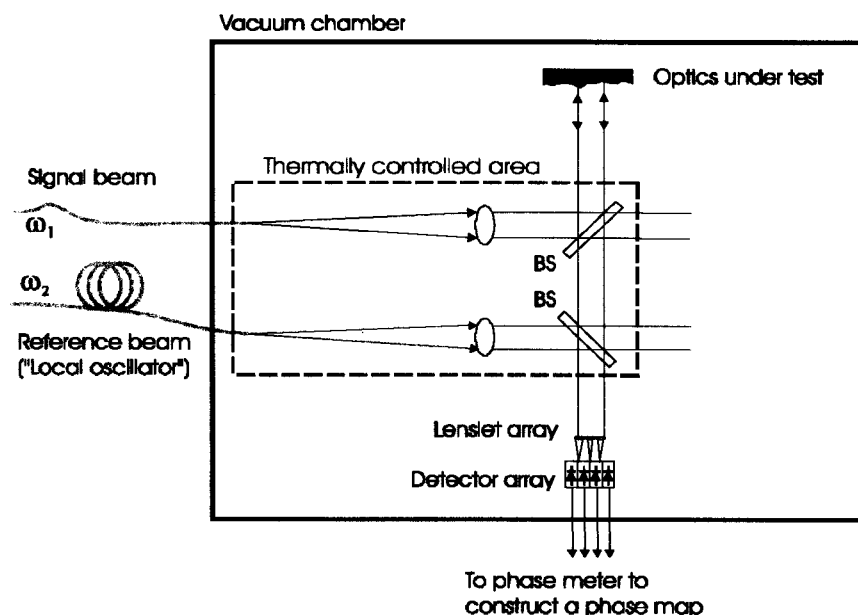
*heterodyne interferometry  
metrology  
nanotechnology*

# Objective

- To measure thermal stability of telescopes and other optical subsystems;
  - measurement of changes in surface figure (wavefront) at subnanometer level ( $\sim 100\text{pm}$  or better).

# Enabling Technology: *COmmon-Path Heterodyne Interferometer (COPHI)*

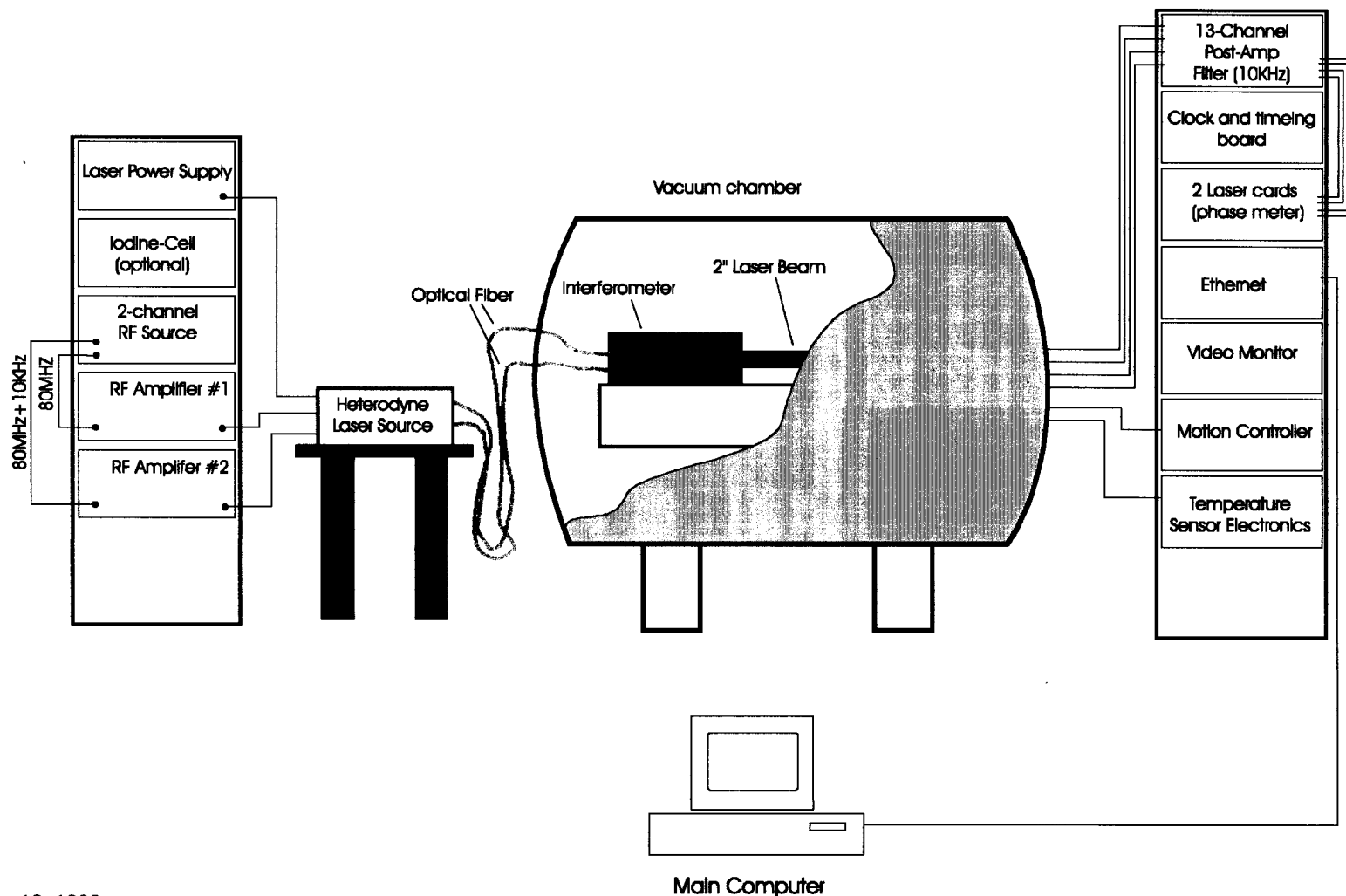
- Measure the heterodyne signal phase between sub-apertures using a 2-D detector array;
- Construct a 2-D phase map (relative surface height);
- Heterodyne detection ensures picometer level measurement.



# Features of COPHI

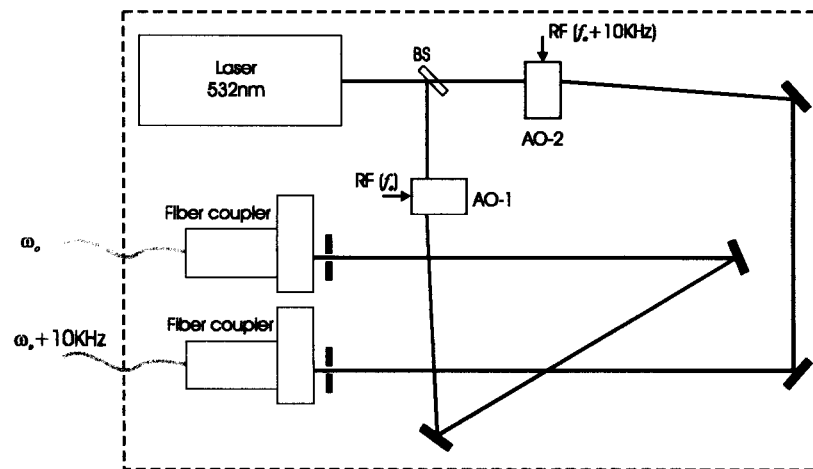
- Common-path reduces:
  - fringe phase error due to laser frequency and power fluctuations;
  - optical path length error caused by structural vibrations (piston mode).
- Wide applications:
  - thermal deformations of optics;
  - beam walk (single mirror, compressor, delay line, etc.);
  - corner cube articulation error;
  - on-board wavefront monitoring, etc.

# Instrument Schematic

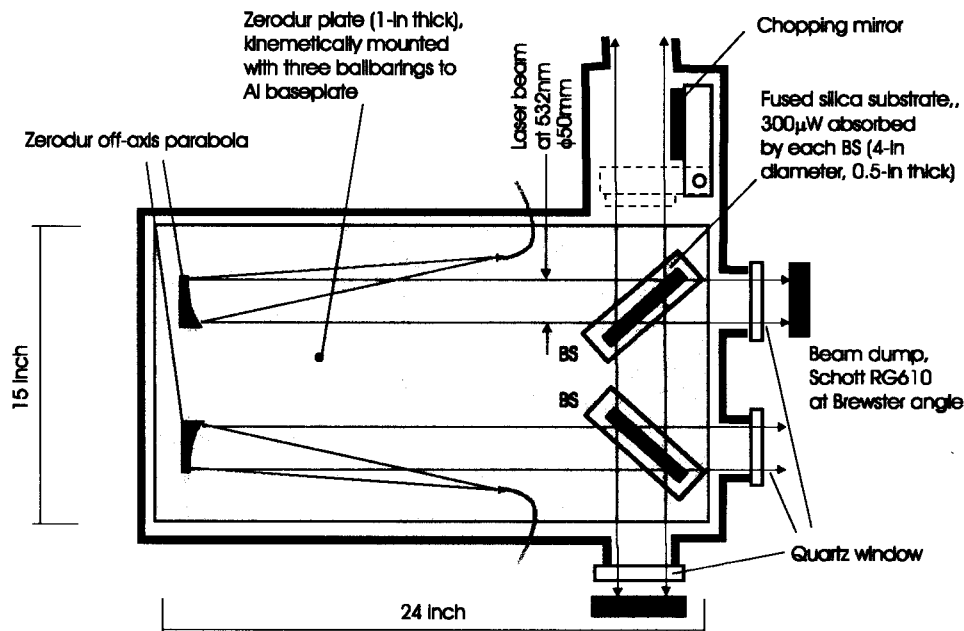


# Heterodyne Laser Source

- Because reference and unknown signals are common mode, laser frequency noise and intensity fluctuations are cancelled.
- Two PM fiber pigtailed output;
- 10KHz heterodyne frequency;
- Heterodyne frequency stability: 1ppm/hr;
- 1:4 power ratio (8mW:30mW);
- $\lambda = 532\text{nm}$ .



# Athermalization of Key Optical Components

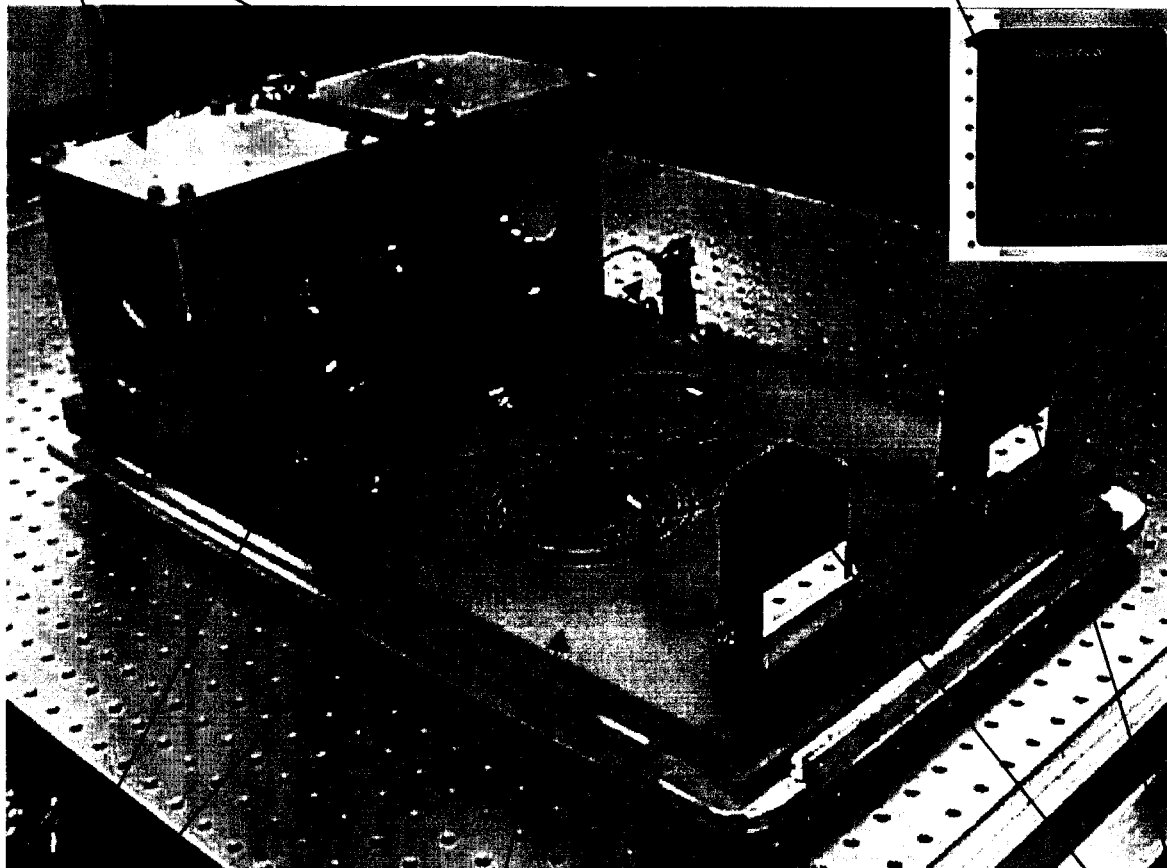


- Use low CTE material such as Zerodur off-axis parabolic reflector to reduce wavefront distortion;
- Zerodur base plate to reduce defocusing error;
- Compromise reflection distortion (CTE only) with transmission distortion (both CTE and  $dn/dT$ ) in selecting substrate material for the two beam splitters;
- Super-Invar micrometer screws on BS mount to maintain pointing stability;
- De-couple radiation from others by:
  - aluminize chopping mirror and parabolic mirrors;
  - quartz window (IR opaque)

# COPHI Collimator Assembly

Beam splitter mounts

Shearing interferogram indicates  
high quality collimation



PM fibers

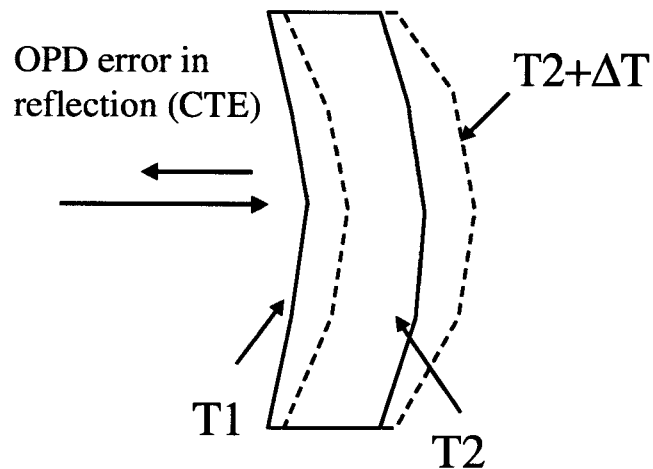
Zerodur plate

Off-axis parabola

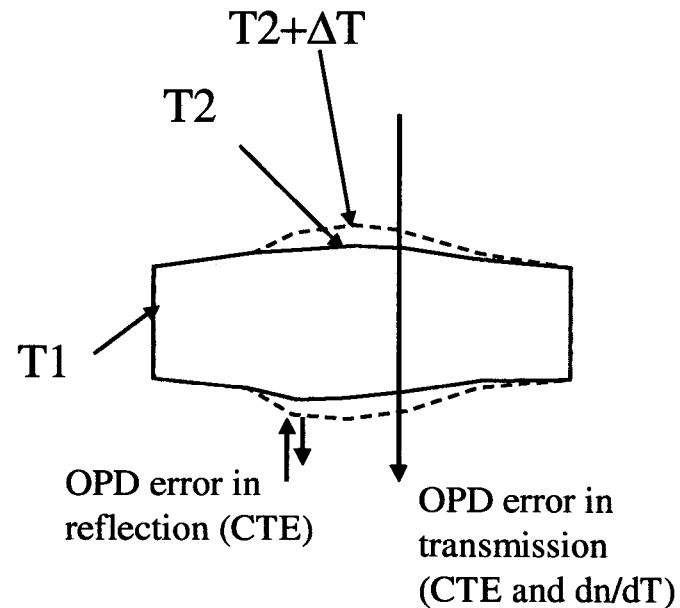


## What We Care About Is the **CHANGE** in Temp Gradient

- Change is much smaller than static temp gradient;
- A simplified model to estimate the required temp gradient stability;
  - Front-back (axial) temp gradient stability;
  - Center-edge (radial) temp gradient stability.



Front-back (axial) temp gradient changes



Center-edge (radial) temp gradient changes

# Reduce Thermal Stability Requirement by Periodic Referencing

- Use a stable reference mirror (“chopping mirror”) to periodically calibrate the wavefront error in the interferometer setup;
- Reduce the thermal stability requirement from 0.x mK/hr to 0.x mK/a few min;
- Positioning repeatability:
  - 1  $\mu\text{m}$ , linear;
  - 1  $\mu\text{rad}$ , angular;

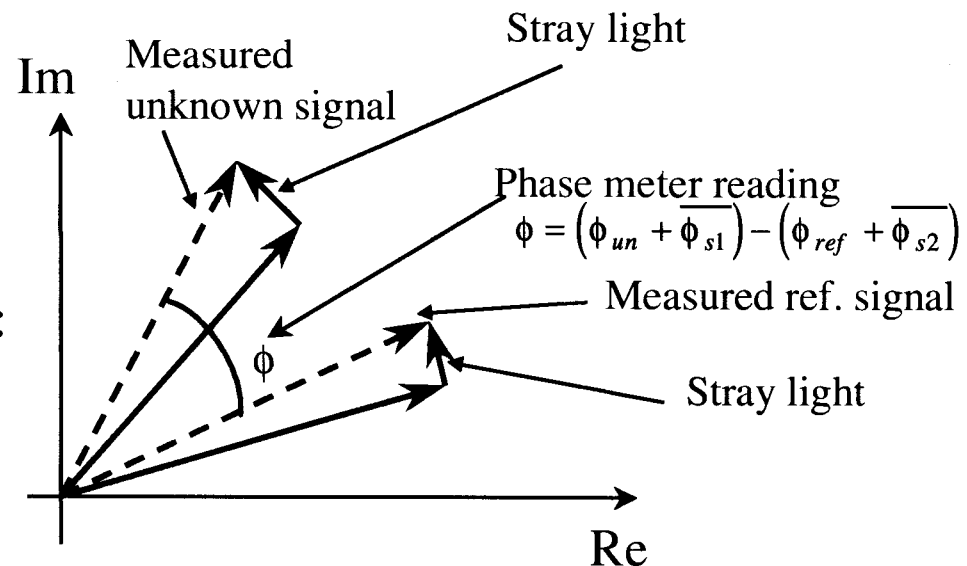


# Stray Light

- Coherent stray light will cause a phase error in the heterodyne signal;
- Only **TIME-VARYING** part of this phase error is important because COPHI is to measure surface deformations, i.e., changes in phase;

$$\frac{d\phi}{dt} = \frac{d}{dt}(\phi_{un} - \phi_{ref}) + \frac{d\overline{\phi_{s1}}}{dt} - \frac{d\overline{\phi_{s2}}}{dt}$$

- The contribution of stray light can be negligible if  $\phi_s$  is constant (including =0)
- Averaging reduces the error:
  - stray light incident angle;
  - detector area;
  - stray light wavefront quality;
  - dithering in time and integrate.



# Stray Light Control in COPHI

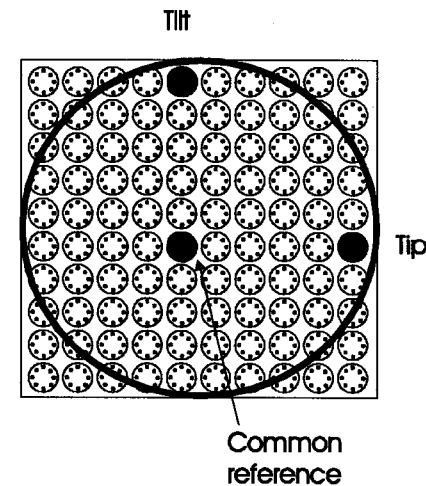
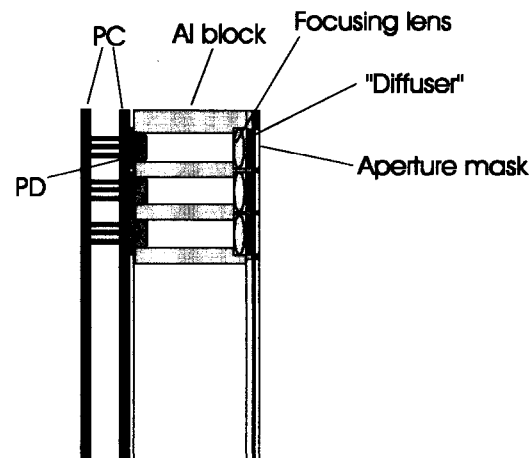
- Reflection from back surface of the beam splitters:
  - 0.5 deg wedge;
  - -30dB reflection (AR coating), -30dB isolation using spatial filtering;
  - average ~100 fringes across 5mm aperture;
  - constant in phase ( $\Delta\theta < 0.002$  rad) because of thermal stabilization, and proportional in amplitude;
  - ~1pm
- Scattering from dust:
  - add a constant phase offset by “static dusts” (such as scratches on optics);
  - need clean environment to avoid “mobile” dusts;
  - not a concern in clean vacuum chamber
- Reflection from fiber tip:
  - APC connector (angle-polished, 16 deg) to launch fiber light;
  - reflected beam off by 32 deg, misses the parabola (f/5, 6 deg half angle);
  - not a concern;
- Reflection from detectors:
  - “spatially incoherent” (phase randomization) by using home-made “diffuser”;
  - not a concern;
- Reflection imaging optics:
  - AR coating (v-type);
  - can tilt lens without losing imaging “quality” (our “camera” has only 10X10 pixels);
  - need to be careful in selecting lenses (curvatures) that don’t send a reflection right into the detector.

# Effects of Vibration

- Insensitive to piston mode because of common path, a big plus;
- Tip/tilt modes ranging from 1Hz to 0.1Hz will cause an error in the constructed surface map:
  - 2-D array pixels are NOT measured at the same time;
  - different rows in the detector array may see different tip/tilt (in the 1 - 10 seconds time frame);
  - need to remove the tip/tilt error from each row before construction of the phase map;
- Our solution:
  - dedicate 2 detectors as tip/tilt sensors;
  - continuously measure the tip/tilt between the measurement and reference wavefronts;
  - remove the tip/tilt error from each row measurement before constructing the surface map.

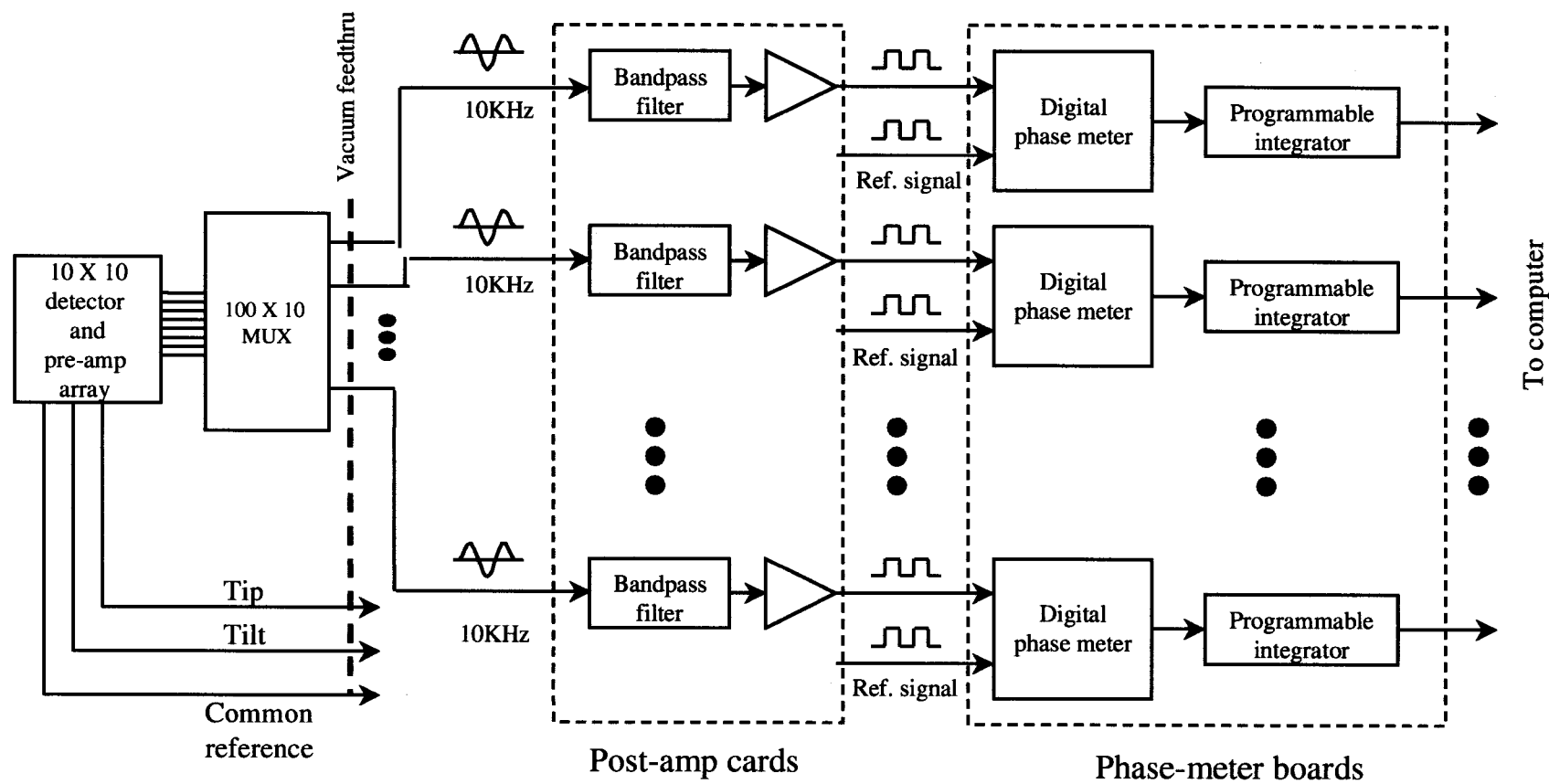
# Detector Array

- 10 X 10 detectors;
  - thermal deformation generally in low spatial frequency;
  - compatible with number of nodal points in thermal modeling of a surface;
- Si PIN photo-diode with low power dissipation amplifier;
- Reference to one common detector;
- Two detectors to measure tip/tilt (0.1-1Hz);
- Printed-circuit boards to align diodes and improve thermal conduction with a copper layer;
- "Diffuser" to achieve more uniform and more stable illumination on the photo-diode active region;
- Aperture positioning tolerance  $\sim 1\mu\text{m}$ .



# DAQ Block Diagram

- Use modified version of current 1-D metrology electronics H/W and S/W;
- 100 X 10 MUX to handle 100 channels;
- 2 high precision phase-meter boards (total 12 channels, 2 used for tip/tilt);
- 2 tip/tilt channels are “on” all the time.

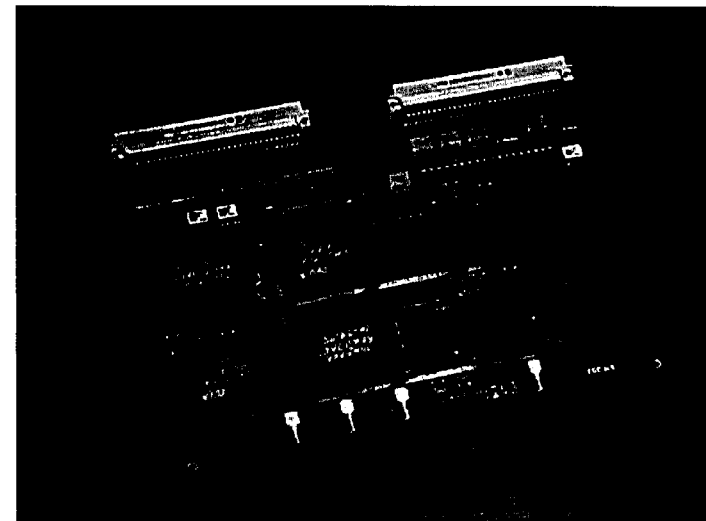




# Data Acquisition Electronics

- A 100 X 10 MUX board in vacuum to switch 10×10 channels sequentially (switching time < 100ms);
- ~ 0.1 mfringe instantaneous phase resolution, and 1  $\mu$ fringe for averaging over 1 sec;
  - optical power about 1 $\mu$ W per channel at  $\lambda=532\text{nm}$ , fringe visibility ~ 0.5;
  - carrier frequency (heterodyne frequency) is 10KHz;
- Stability of total delay (from where photo-electrons are generated to phase meter) <200 ps/hr between ref and unknown channels.

## High Precision Phase-meter Board



# Summary

- Proposed COPHI concept for subnanometer surface metrology;
  - measurement of changes of surface figure and wavefront stability;
- Common-path reduces:
  - fringe phase error due to laser frequency and intensity fluctuations;
  - optical path length error caused by structural vibrations (piston mode).
- Integration and test under way;
- Broad potential applications:
  - thermal deformations of optics; beam walk (single mirror, compressor, delay line, etc.); corner cube articulation error; and on-board wavefront monitoring.